Compact, Lightweight Payload for Covert Data Link using a Multiple Quantum Well Modulating Retro-reflector on a Small Rotary-Wing Unmanned Airborne Vehicle

by

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ABSTRACT

In this paper, we describe progress in the development of the NRL Multiple Quantum Well modulating retroreflector including a description of recent demonstrations of an infrared data link between a small rotary-wing unmanned airborne vehicle and a ground based laser interrogator using the NRL multiple quantum well modulating retro-reflector. Modulating retro-reflector systems couple an optical retro-reflector, such as a corner-cube, and an electro-optic shutter to allow two-way optical communications using a laser, telescope and pointer-tracker on only one platform. The NRL modulating retro-reflector uses a semiconductor based multiple quantum well shutter capable of modulation rates up to 10 Mbps, depending on link characteristics. The technology enables the use of near-infrared frequencies, which is well known to provide covert communications immune to frequency allocation problems. The multiple quantum well modulating retro-reflector has the added advantage of being compact, lightweight, covert, and requires very low power. Up to an order of magnitude in onboard power can be saved using a small array of these devices instead of the Radio Frequency equivalent. In the described demonstration, a Mbps optical link to a unmanned aerial vehicle in flight at a range of 100-200 feet is shown. Near real-time compressed video is also demonstrated at the Mbps level.

KEY WORDS: Modulating Retroreflector, Multiple Quantum Well Modulator, Retroreflector Communications, MQW Retroreflector

1. INTRODUCTION

Free space optical communications has emerged in recent years as an attractive alternative to the conventional Radio Frequency (RF) approach. This evolution has been due to increasing maturity of lasers and compact optical systems which enable exploitation of the inherent advantages of the much shorter wavelengths characteristic of optical and near infrared carriers. These advantages include: large bandwidth, low probability of intercept, immunity from interference or jamming, frequency allocation relief, and in many cases, smaller, lighter payloads. For a conventional optical link, a good to high quality telescope which provides relatively accurate pointing and tracking capability as well as a robust laser with sufficient power, temperature stabilization, and requisite electronics are needed in addition to the usual modulating and demodulation and control and acquisition instrumentation and software. There are many applications, however, where reducing the parasitic payload requirements for the onboard communications system would be advantageous.

By coupling a simple modulator with an optical retroreflector and providing the data-gathering instrumentation signals to the driver, an elegantly simple, low power and compact communications transceiver can be configured. Essentially, the retroreflector with related electronics is all that is mounted on the data-gathering platform to demonstrate a key part of the

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communications link. A remotely located transmitter/receive system consisting of a laser, telescope, and detector of sufficient power, gain, and sensitivity would provide the means to interrogate the platform-mounted modulating retroreflector. By virtue of the inherent nature of the retroreflector, the incident light is reflected to the co-located receiver but carries the modulated signal imposed by the shutter. When the device is configured into an array, pointing requirements are also substantially relaxed. The Field-of-View (FOV) of a typical device is of the order of 20 degrees. However, the FOV can be expanded arbitrarily using an array of devices to accommodate pointing and acquisition requirements of the interrogator. The mass increases to some extent but a five-element device with a FOV of 60 degrees can be configured at less than 100 grams. No gimbaled telescope or laser is flown. Figure 1 illustrates the concept. The idea was successfully demonstrated by Swenson, et. al., using a balloon in flight with a Ferro Liquid Crystal (FLC) shutter in 1996 [1].

The concept of a modulating retroreflector is an old one. However, until recently, modulators have not been available which could support a viable link. The shutter must have a high switching speed, low power consumption, large area, wide field-of-view and high optical quality. In addition, it must be functional at wavelengths where good laser sources are available, be radiation-tolerant (for space applications) and rugged. Mechanical shutters, for example, are too slow and heavy, and FLC devices are, unfortunately, too slow (kilo bits per second) and are not robust by comparison. To extend modulating retro-links to data rates of mega-bits per second and higher, and to payloads which must operate over large temperature swings characteristic of installation out of doors and in space, NRL has pursued the use of a different type of electro-optic shutter: a semiconductor-based optical switch based on GaAs Multiple Quantum Wells (MQW)[2-5].

2. MULTIPLE QUANTUM WELL MODULATORS

Semiconductor multiple quantum well (MQW) modulators are one of the few technologies that meet all the requirements described above [6]. MQW technology is the basis for commercially available laser diodes. When used as a shutter, MQW technology offers many advantages. It is robust and all-solid state. In addition, it operates at low voltages (less than 20 V) and low power (less than 1 Watt). Most importantly, it is capable of very high switching speeds. MQW modulators have been run at data rates in the Gbps regime in fiber applications. The MQW modulators used in this program were grown at NRL by molecular-beam epitaxy (MBE). The details of the growth and some optimizations used to improve the material quality are discussed in Ref. 7. Briefly, the modulators consist of about one hundred very thin (~10 nm) layers of several semiconductor materials, such as GaAs, AlGaAs, and InGaAs, epitaxially deposited on a large (3 inch diameter) semiconductor wafer. Electrically, they take the form of a P-I-N diode. Optically, the thin layers induce a sharp absorption feature at a wavelength that is determined by the constituent materials and the exact structure that is grown.

When a moderate voltage (~15V) is placed across the shutter in reverse bias, the absorption feature changes, shifting to longer wavelengths and dropping in magnitude. Thus, the transmission of the device near this absorption feature changes dramatically. Figure 2 shows absorbance data for an InGaAs MQW modulator designed and grown at NRL for use in a modulating retro-reflector system. The figure illustrates how the application of a moderate voltage shifts the transmittance. Hence, a signal can be encoded in an On-Off-Keying format onto the carrier interrogation beam.

This modulator consists of 75 periods of InGaAs wells surrounded by AlGaAs barriers. The device is grown on an n-type GaAs wafer and is capped by a p-type contact layer, thus forming a P-I-N diode. This device is a transmissive modulator designed to work at a wavelength of 980 nm, compatible with many good laser diode sources. GaAs/AlGaAs modulators that work at 850 nm have also been grown. These materials have very good performance, and operate in reflection architectures. Choice of modulator type and configuration architecture is application-dependent.

Once grown, the wafer is fabricated into discrete devices using a multi-step photolithography process consisting of etching and metallization steps. The NRL experimental devices have a 5-mm aperture, though larger devices are possible and masks for one centimeter devices are currently being designed as well. It is important to point out that while MQW modulators have been used in many applications to date, modulators of such a large size are very uncommon and require special fabrication techniques. Figure 3 shows a block diagram and photo of a wide aperture MQW shutter designed, grown, and fabricated at NRL.

MQW modulators are inherently quiet devices, faithfully reproducing the applied voltage as a modulated waveform. An important parameter is contrast ratio, defined as I_{max}/I_{min}. This parameter impacts the overall signal-to-noise ratio. Its magnitude depends upon the drive voltage applied to the device and the wavelength of the interrogating laser relative to the exciton peak. The contrast ratio increases as the voltage goes up until a saturation value is reached. Typically, the

modulators fabricated at NRL have had contrast ratios between 1.75 to 1 to 4 to 1 for applied voltages between 15V and 25V, depending on the structure.

There are three important considerations in the manufacture and fabrication of a given device. The first is inherent maximum modulation rate vs. aperture size; the second is electrical power consumption vs. aperture size; and the third is yield. The fundamental limit in the switching speed of the modulator is the resistance-capacitance limit. A key trade then is area of the modulator vs. area of the clear aperture. If the modulator area is small, the capacitance is small; hence the modulation rate can be faster. However, for longer ranges on the order of several hundred meters, larger clear apertures are needed to close the link. For a given modulator, the speed of the shutter scales inversely as the square of the modulator diameter.

Second, when the drive voltage waveform is optimized, the electrical power consumption of a MQW modulating retro-reflector scales as:

$$D_{\mathrm{mod}}{}^{4} \cdot V^{2} B^{2} R_{S} \tag{1}$$

where D_{mod} is the diameter of the modulator, V is the voltage applied to the modulator (fixed by the required optical contrast ratio), B is the maximum data rate of the device, and R_S is the sheet resistance of the device. Thus a large power penalty may be incurred for increasing the diameter of the MQW shutter.

The third issue is yield. MQW devices must be operated at high reverse bias fields to achieve good contrast ratios. In perfect quantum well material, this is not a problem. However, the presence of a defect in the semiconductor crystal can cause the device to break down at voltages below those necessary for operation. Specifically, a defect will cause an electrical short will prevent development of the necessary electrical field across the intrinsic region of the PIN diode. The larger the device, the higher the probability of such a defect. Thus, if a defect occurs in the manufacture of a large monolithic device, the whole shutter is lost.

To address these issues, NRL has designed and fabricated segmented devices as well as monolithic modulators. That is, a given modulator might be "pixellated" into several segments, each driven with the same signal. This technique means that speed can be achieved as well as larger apertures. The "pixellization" inherently reduces the sheet resistance of the device, decreasing the RC time. Furthermore, electrical power consumption is reduced. For example, a one centimeter monolithic device might require 400 mW to support a one Mbps link. A similar nine segmented device would require 45 mW to support the same link with the same overall effective aperture. Finally, yield is increased. That is, if a single "pixel" is lost due to defects but is one of nine or sixteen, the contrast ratio necessary to provide the requisite signal-to-noise to close a link is still high. There are considerations that make fabrication of a segmented device more complicated which include bond wire management on the device, driving multiple segments, and temperature stabilization. A transmissive device with nine "pixels" with an overall diameter of 0.5 cm was shown to support over 10 Mbps. A representative trace is shown in Figure 4.

An additional important characteristic of the modulator is its optical wavefront quality. If the modulator abberates the beam, the returned optical signal will be attenuated and insufficient light may be present to close the link. In Figure 5, an infrared interferometric measurement of a one-cm piece of the InGaAs modulator is shown. As can be seen, the optical quality of the device is very good and should not deleteriously impact system performance.

3. SYSTEM CONSIDERATIONS

In practice, except for close ranges, for a modulating retro system, the link rather than the modulator limits performance. For a conventional corner-cube modulating retro-reflector, MQW technology should allow data rates in the tens of mega-bits per second, depending on range and the interrogator system.

For a diffraction-limited system, the optical power, retro-reflected from the small platform back to the large platform scales as:

$$\frac{P_{laser} \cdot D_{retro}{}^{4} \cdot D_{rec}{}^{2} \cdot T_{atm}{}^{2}}{\theta_{div}{}^{2} \cdot R^{4}} \tag{2}$$

Where P_{laser} is the power of the laser transmitter on the large platform, D_{retro} is the diameter of the modulating retro-reflector on the small platform, D_{rec} is the diameter of the receive telescope on the large platform, T_{atm} is the loss due to transmission through the atmosphere, θ_{div} is its divergence of the transmit beam, and R is the range between the two platforms.

The strongest dependencies are on the range and the retro-reflector diameter, both of which scale as fourth powers. Retro-reflector links fall off more strongly with range than conventional links because of their bi-directional nature. The strong dependence on retro-reflector diameter occurs because increasing the size of the retro-reflector both increases the optical power intercepted and decreases the divergence of the returned optical beam. The link is very clearly a compromise between a large retro-reflector aperture to maximize the returned optical power and a small modulator to maintain data rate while keeping the consumed electrical power, low. This trade is mitigated to some extent by using segmented devices discussed above. When all the segments are driven in parallel, the power consumption may be comparable to a monolithic device, but the modulation rate of the smaller device will be exploited while enabling the larger aperture.

Channel losses are an additional consideration, particularly for terrestrial applications. Propagation through the atmosphere can induce losses due to absorption and scattering. In addition, the use of a near-infrared link means that it will not operate under all weather conditions. However, operability in the one micron regime is greater than in the visible. Figure 6 compares visibility through smoke and haze in the visible to visibility at 1.06 microns. These images are of a fire over a town in northern California taken by the JPL Airborne Visual Infrared Imaging Spectrometer (AVIRIS) [8,9], which records data in 224 wavelength bands with both the resolution and center-to-center band spacing of about 10 nm. It is clear from these photos that operation in the near-infrared extends the range of viable operation for an application such as remotely observed video. Propagation through the atmosphere at different wavelengths is compared in Figure 7. In this figure, propagation on a clear day is compared with propagation on a hazy day. The traces include absorption, Rayleigh scattering, and aerosol scattering losses for a retro-reflected link through the full atmospheric channel.

The device is uniquely suited for applications where platform asymmetry is tolerated or preferred and where a compact, low power payload is required. Serving as the communications payload on an Unmanned Aerial Vehicle (UAV), which can be remotely interrogated on the ground or in the air is an ideal candidate concept. Video or other forms of data can be obtained onboard the UAV, the signal translated to drive voltages required by the modulator, and interrogated by a remotely located laser transmitter/receiver system. The onboard system would then activate the modulator and the retroreflected signal would be returned to the interrogated with the modulation from the video or other data type impressed upon the carrier beam. When the modulator is configured into an array, the pointing requirements are considerably relaxed and the onboard FOV increased to accommodate the incoming beam with relaxed steering requirements. By eliminating the need for a gimbaled telescope, optical antenna, and heavy power supply, the communications package now enables use of very small platforms or opens up the payload geography for other data acquisition payloads. Figure 8 illustrates how the device might be incorporated into airborne reconnaissance in this way.

4. NRL FIELD TESTS

Successful implementation of a modulating retro-reflector link requires the integration of the device onto a platform as well as the ability to close a link while in flight. As a first step in developing an operational modulating retro-reflector communications link, NRL conducted two field tests to date with follow-on tests planned. The aim of these tests was to demonstrate a short-range link to a platform that carried no active pointing system and indeed had relatively low platform stability. The tests were conducted in the fall of 1999 and in the winter of 2000 at the NRL Chesapeake Bay Detachment facility in Maryland.

A 0.5 cm diameter InGaAs transmissive MQW modulating retro-reflector was mounted on a small rotary-wing unmanned airborne vehicle [10]. The modulating retro-reflector was placed on the tail of the UAV pointing down. Also mounted on the UAV were a camera, microprocessor, frame grabber and electrical drive circuitry for the modulator. The microprocessor could be programmed to send a pseudo-random bit stream at different bit rates ranging from 400 Kbps to 2 Mbps to the modulating retro-reflector. The UAV was flown at an altitude of about 35 meters and a range of 35 to 65 meters from the transmit/receive laser. The conditions for the test were somewhat adverse with a light rain, fog and low visibility. The second test was conducted with snow cover and in icy outdoor conditions. Nonetheless, due to the short range and the infrared wavelength of the laser no atmospheric effects were observed. Figure 9 below shows the UAV, which is about 1-1/2 meter long.

The modulator used in the field tests was a monolithic 75 period InGaAs/AlGaAs MQW with an exciton resonance at 981 nm. The modulator was affixed to a mount centered above a corner-cube retro-reflector. Wire bonds to the p and n contact layers on the modulator were used to bias the modulator. The modulator/retro-reflector assembly shown in Figure 10 was ringed by infrared LEDs that were used to provide a beacon for acquisition and tracking of the UAV. The six-element array was populated with 880 nm LEDs. Light emitted from this array at a half angle of 15 degrees and served as a beacon for the tracking camera.

In addition to the modulator, the UAV carried video and driving electronics. The challenge in the design of the payload electronics was to design a lightweight but flexible payload that could meet the unique requirements of our demonstration. The tests were conducted at NRL's Chesapeake Bay facility located by the ocean. The payload had to survive vibration, oil mist, shock, fog, mist, and icy conditions.

The modulator used in the payload required an approximate 15 Volt swing to achieve a sufficient optical contrast between the on and off states. Electrically, the modulator can be modeled as an approximate 2 nF capacitor in series with a 5 ohm resistor. The drive circuitry consisted of a 15 - 17 volt power source, an Elantec 7202 driver and a 0.1 μF bypass capacitor. The Elantec part was chosen for its ability to drive a capacitive load at 1 - 10 MHz. A Field Programmable Gate Array (FPGA) microprocessor was used to encode the data. In addition, the FPGA performs framing functions on the data, generation of the pseudo random code for bit error tests and the required encoding of the video data needed for DC balance. The user can modify the FPGA quickly to change encoding method, to add error correction, and to change the frame format. Its flexibility lent itself well to the NRL test requirements for on-site modifications of bit streams. An off-the-shelf frame grabber card collected the video data and prepared it for transport. The card receives an NTSC signal from an on board camera and passes the data via the PC/104 bus to the FPGA card.

The payload electronics for the modulating retro experiment can be divided into two sections. The first consists of the modulator, its drive electronics, and the electronics used for generating and encoding data. A PC/104 form factor was chosen for data collection and encoding electronics because of the ample supply of off-the-shelf PC/104 cards. These cards both meet the stringent requirements of cost and vibration survivability as well as enabling the user to make quick changes in the lab and the field. The PC/104 stack consists of an FPGA-based processor card that is used to encode, frame and send the data to the modulator, a frame grabber card which collects video data from a camera and a X86 class card. The X86 card, which runs Linux, is used to boot the FPGA card, run scripts, and collect and store video data. The card also provides a communication link to the outside world via a PPP link connected to the serial port. This setup created a very flexible platform that can be quickly be re-configured to meet requirements of different tests. The configuration can be used to test any new configurations before implementation in a small and compact package.

To close the optical link, a laser must illuminate the UAV and the returned optical signal must be collected and focused onto a detector. We used a very simple optical configuration. A 100 mW laser diode operating at 976 nm was fiber coupled to a collimator. The beam was given a relatively broad divergence of 3 milliradians to avoid laser safety issues with low flying aircraft. The outgoing beam passed through a 7.62 cm diameter 50 percent beam splitter. Half the light went out and half went into a beam dump. The retro-reflected light was reflected by this beam splitter onto a 2-inch diameter lens where it was focused onto a silicon avalanche photodiode. A 10 nm bandwidth optical filter was used to remove background sunlight. The resulting signal was amplified by a 3 MHz bandwidth amplifier and read out on an oscilloscope or fed into the receive electronics for bit error rate tests or video display.

The optical assembly was mounted on a motorized gimbal to allow for active tracking of the UAV. The video tracking system utilized for the modulating retroreflector demonstration used a video tracker with a computer controller. A PC-based laptop served as the controller, which communicated with the tracker over an RS 232 line. A pan-and-tilt gimbal was controlled by the same laptop computer via the RS 232 serial connection. The transmit/receive optics and tracking and acquisition cameras were mounted on the gimbal. The tracking camera was a high sensitivity CCD camera with a narrow FOV, with incident light filtered by a 830 nm long pass filter and an 880 nm bandpass filter. The acquisition camera was a wide FOV miniature CCD camera and was unfiltered. The tracker controller sets the tracking threshold and gate area along with the line-of-sight offset. This offset is picked to maximize return from the modulator. It then commanded the tracker to work in "Auto Track" mode, which caused the tracker to begin tracking a target as soon as it was acquired without further command. Once the tracker was set up for the demonstration, changes through the computer controller were no longer needed.

The tracking software began in manual mode. The user moved the gimbal using the computer mouse or joystick. The operator used the acquisition camera to find the UAV target. Once the tracker acquired the target, it initiated auto-tracking by sending a TTL signal to the gimbal controller. This signal was sent to the computer through an analog-to-digital data acquisition board and the tracking loop was initiated. The tracker provided elevation and azimuth errors as voltages from –5 V to +5 V. There is a linear correlation between the tracker signal and the target distance from the line-of-sight tracking point. These voltages were read through the same data acquisition board and translated to motorized steps to move the gimbal. Elevation and azimuth offsets were updated at a 60 Hz rate. If track was lost, the software waited a prescribed time interval and then returned to the manual acquisition mode. The entire transmit/receive assembly is shown in Figure 11.

In flight, the angle between the laser and the UAV changed rapidly for short ranges (on the order of 35 meters). In addition, the attitude of the UAV also changed rapidly due to weather conditions. Despite these challenges, a strong return signal was received as long as the laser beam was directed into the acceptance angle of the retro-reflector, which was approximately 20 degrees. The beam returned from the modulating retro-reflector had a divergence of approximately one half milliradian and was passively directed back to the transmit/receive assembly without any need for acquisition and pointing on the UAV.

A typical return from the field tests is shown in Figure 12. In the two tests conducted, the modulation rate received in flight was 400 Kbps and 910 Kbps. However, the modulator and detector bandwidth and the returned signal level were sufficient to support a 2 Mbps link at low bit error rates. The modulator consumed 40 mW of electrical power at this modulation rate.

Future tests will demonstrate higher data rates and video transmission from the UAV. Several modifications to the payload and Tx/Rx designs are being made to effect these goals. First, the payload will be replaced by an array of modulating retroreflectors. A lightweight holder with a space-qualified heritage was designed and fabricated at NRL which is 10 grams complete. This mass includes the retro, holder, modulator, cover plate, and wiring leads. A photo of the new mount is shown in Figure 13. The holders will be populated and arranged into a lightweight array which will replace the ring of LEDs used in the initial tests. This modification to the payload will enable self-tracking from the UAV and will increase the FOV to 60 degrees. The larger onboard FOV will further relax onboard pointing and tracking requirements. It should be noted that tracking and acquisition functions will be consolidated onto a single laptop in future tests but were separated initially to develop and test control algorithms which had to function in parallel in real-time.

5. VIDEO COMMUNICATIONS AND DATA LINKS

The NRL MQW modulating retroreflector has been shown to support 10 Mbps at a Bit Error Rate (BER) of better than 10^{-6}. The device was also demonstrated to support uncompressed near-realtime black and white video over a 17-meter link in 1998 [4]. After the field tests, the driver and receiver electronics were modified to support JPEG compressed video across a modulating retroreflector link in the laboratory. This was done to demonstrate that a higher quality video link could be easily supported by a modulating retro link than was previously shown. In this demonstration, compressed color video was transmitted at 8 frames per second at a rate of 1.2 Mbps across the laboratory spanning several meters. The 980 nm transmission modulator with retroreflector used in the field tests was used in these bench tests as well. The driver electronics were substantially modified however, to drive the modulator at the requisite rates. The receive software was modified as well.

The compression and decompression were performed with an off-the-shelf card from Linux Media Labs containing the Zoran 36060 CODEC. Two major modifications were required to the receiver electronics and software. We found it necessary to use “bit stuffing” on the outgoing video stream to further reduce problems with a running stream of 1’s or 0’s. We also found it necessary to modify the driver for the Linux Media Labs compression card such that it would recover from bit errors. Frame recovery rate was ultimately limited by electronics not by the device, which in previous tests demonstrated performance at 12 Mbps.

Key to this effort was demonstration that compressed color video can be transmitted over a modulating retroreflector optical system at megabit per second rates. Eight frames per second is certainly adequate to communicate scene intelligence and situational awareness to the interrogator location.

6. CONCLUSIONS

It has been shown that a Multiple Quantum Well-based modulating retro-reflector can support Mbps data rates and enable a very small platform to passively close an optical data link. The use of such modulators coupled with a simple optical

retroreflector can allow much higher bandwidth communications for a substantially smaller payload than is typical. In addition, the resulting link is covert, difficult to jam, and immune from the frequency congestion problems to which RF communications are susceptible.

The NRL device has been demonstrated to support over 10 Mbps in a high signal level regime and captured data rates of 400 kbps and 910 kbps on a UAV in flight. Data was transferred over about 35 meters in non-ideal weather conditions. Near-real-time color video using JPEG compression was also demonstrated using the device which transmitted data over several meters at 8 fps over a 1.2 Mbps link. The data rate was ultimately limited by electronics, not the device.

Many applications will require much longer range links than has been demonstrated. Such links will require narrower outgoing beam divergence and larger receive telescopes. The effect of the atmosphere will also play a much larger role in long distance terrestrial links. Nonetheless, link analyses based upon this technology show that with modest power lasers terrestrial links with ranges of tens of kilometers and data rates from 1 to 10 Mbps are possible. Moreover, the modulating retro-reflector systems needed to support such a link are only slightly larger than the one we have demonstrated. The system improvements necessary for longer-range links are primarily on the interrogator side where the very sophisticated systems already developed for conventional free-space optical communication systems can be adapted.

An optical communications link is always susceptible to cloud cover and heavy rain or fog. However, many applications for this device, such as surveillance, are often done in clear weather conditions or below the cloud deck. In addition, operation in the near-infrared offers more functional utility through smoke and mist than does transmission in the visible.

Use of the device as a relay payload in air-to-UAV links may avoid these problems and expand its utility to increase path diversity for non-rf links. An interesting benefit of this technology is that, unlike conventional optical communications, it is not necessarily point-to-point. One modulating retro-reflector can be interrogated simultaneously by many lasers, allowing one node to distribute information to many sites. An array of modulating retros can provide a quasi-broadcast capability while maintaining a compact, covert link.

Other applications for the NRL MQW modulating retroreflector include space-to-space inter-satellite links where one satellite could now be a microsatellite or smaller. Alternately, more of the payload's topography could be used for instrumentation rather than communications. Another application is to use the device as a means to identify multiple objects in space using a unique frequency tag. Once the object is identified, tracking and acquisition can be further facilitated by the use of the device's inherent ranging capability in combination with its data transfer function. Use as a compact low power sensor embedded in an area hostile to humans and then interrogated remotely from the air or space is another possible application. Finally, the device can serve as a probe to study atmospheric effects on retroreflected modulated signals through turbulence and atmosphere. As small platforms proliferate in both scientific and military applications, many applications for modulating retro-reflector systems can be envisioned.

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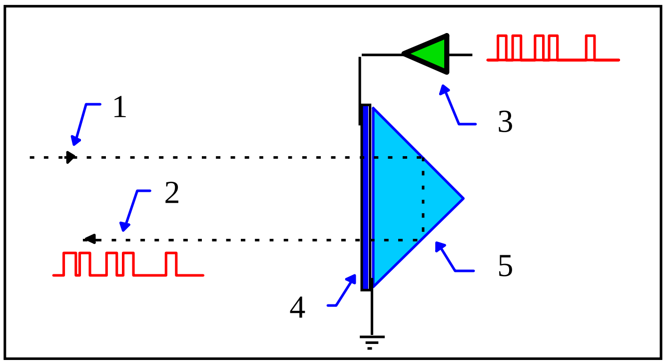


Figure 1. A modulating retroreflector using a transmissive device is illustrated, where (1) is the interrogation beam; (2) is the retroreflected beam; (3) is the drive signal from the data source; (4) is the modulator; and (5) is a retroreflector.

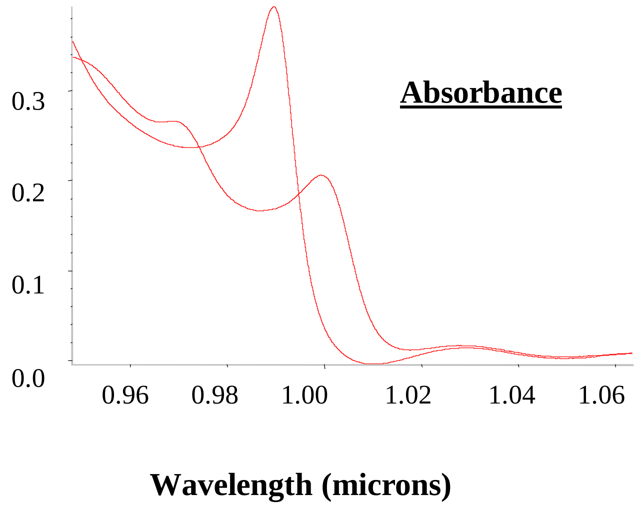
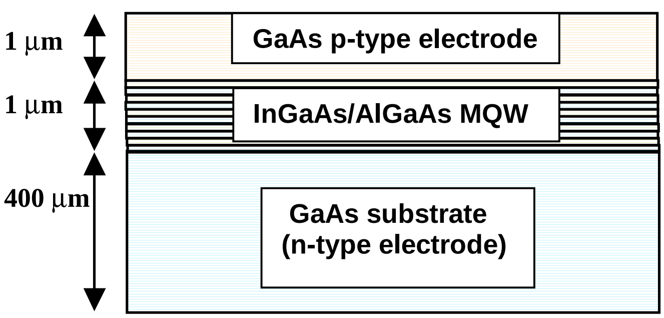


Figure 2. Absorbance vs. Frequency is shown. In its quiescent state the MQW shutter blocks the transmission of incident light. When a moderate voltage is applied, the absorbance shifts and light is transmitted through to the retroreflector.



(a)

(b)

Figure 3. (a) A schematic of a MQW modulator is shown. The GaAs material is grown in alternating layers with active regions about one micron thick. (b) A fabricated ½ cm transmissive device is shown. The NRL large aperture MQW devices operate between 850 nm and 1.06 microns to date.

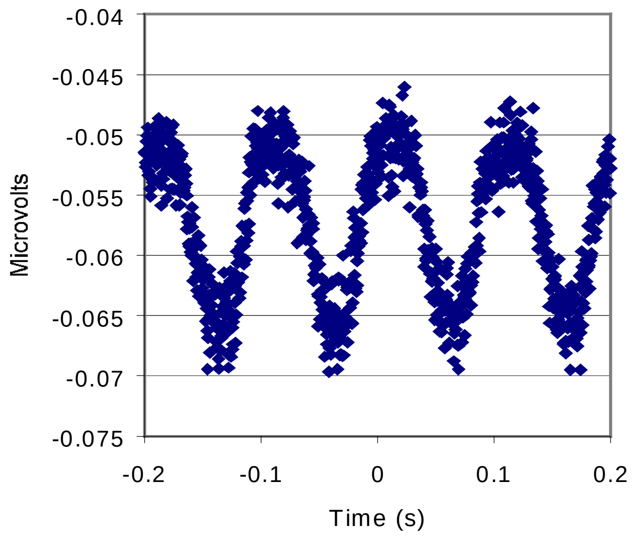


Figure 4. Amplitude vs. time for a nine-"pixel" modulator is shown. The trace shows that modulation rates on the order of 10 Mbps can be supported easily with the device.

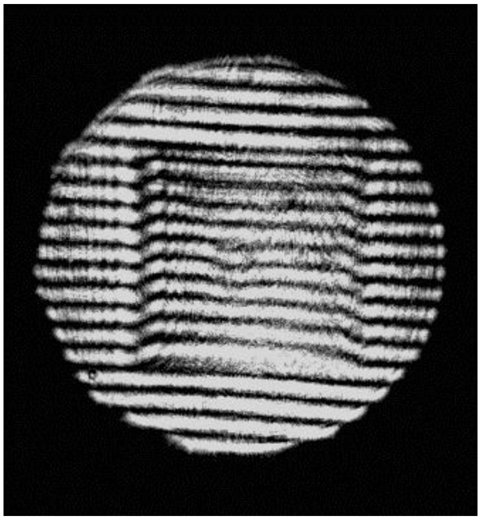
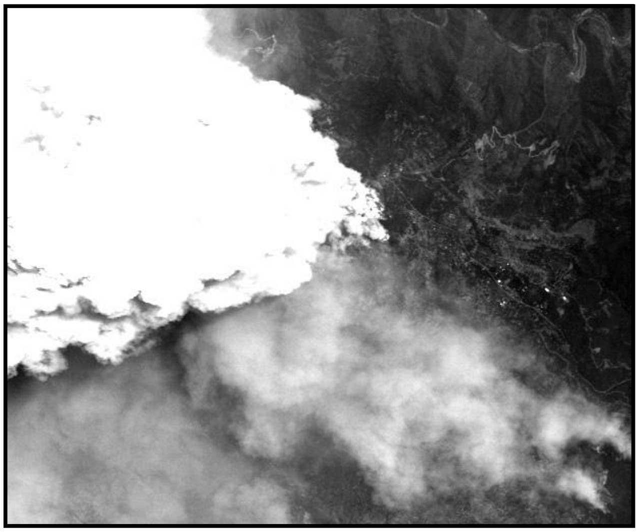


Figure 5. An interferogram of a 1-cm InGaAs transmissive MQW modulator is shown. The ripples around the square are edge effects around the sample. It can be seen that the surface is relatively good and should not deleteriously impact system performance.



(a)

(b)

Figure 6. Imaging data obtained over a town in northern California is shown. Transmission through smoke and haze is evident at 1.06 microns but blocked in the visible. Data was obtained using the JPL AVIRIS hyperspectral camera.

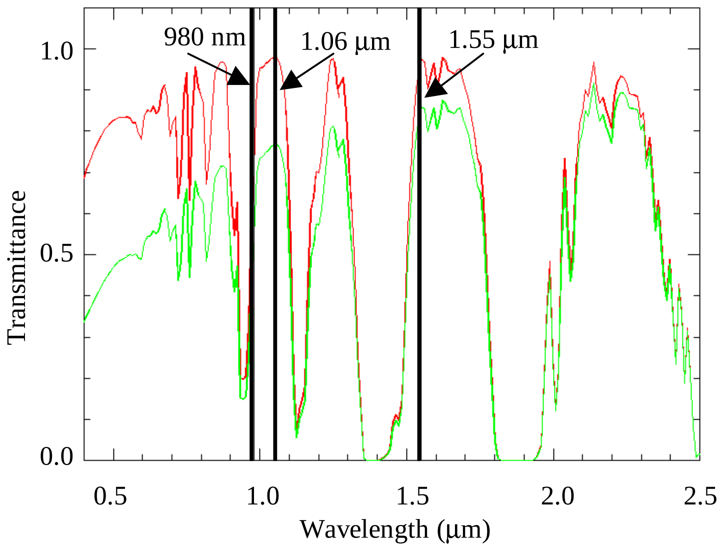


Figure 7. Transmission curves are shown for a clear day (top trace) and for a hazy day (attenuated trace). These are two-way transmission data through the entire atmospheric channel and include losses from absorption and from Rayleigh and Mie scattering. It can be seen that at 1.06 microns and at 1.55 microns, there is a transmission "window" for viable data links.

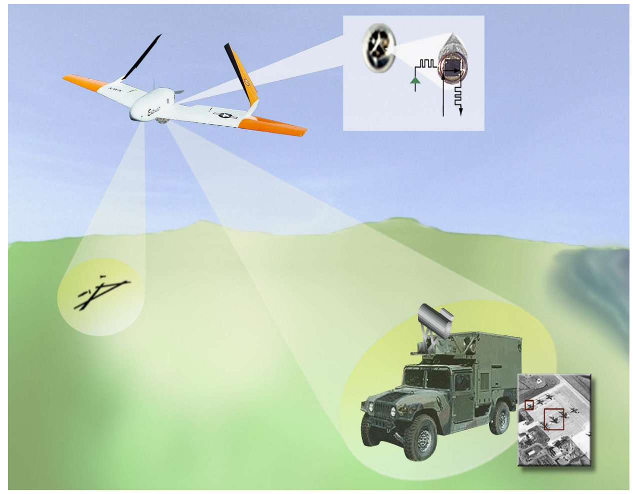


Figure 8. The MQW modulating retroreflector incorporated into an airborne reconnaissance concept using an Unmanned Aerial Vehicle is shown above. When configured into an array, the MQW modulating retroreflector concept significantly reduces the parasitic payload requirements for the onboard communications system.

Figure 9. The small UAV used in the NRL field tests is shown above. The payload was attached to the tail and was designed to be lightweight but flexible to accommodate different experiments.

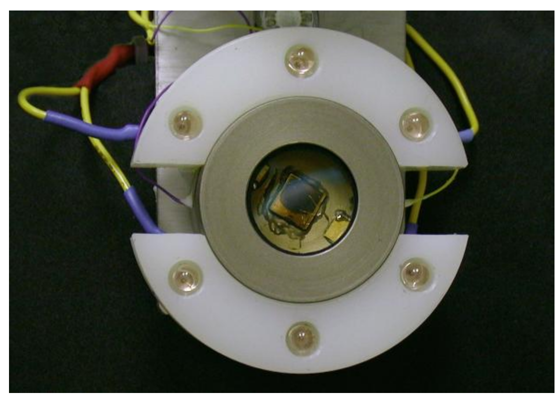


Figure 10. The payload is shown above. A modulating retroreflector mounted and ringed by standard Light Emitting Diodes. The LEDS were used for tracking and acquisition for first tests and will be replaced with modulating retros in subsequent tests.

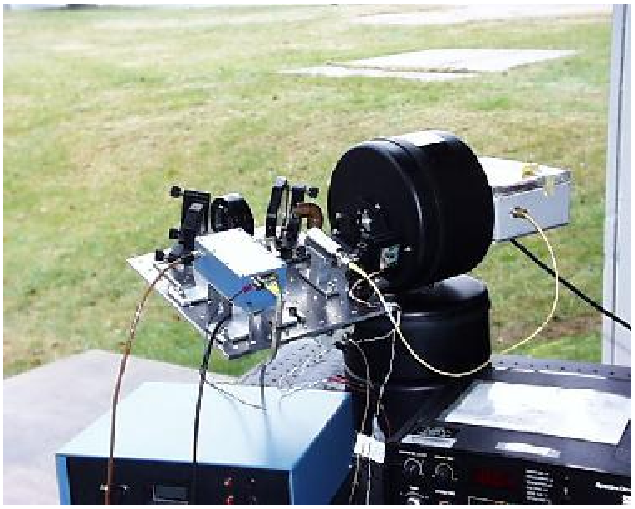


Figure 11. The transmit/receive assembly used in the NRL MQW field tests is shown. (a) The laser diode light is coupled into a fiber which is connected to the lens system. (b) The transmitted then retroreflected light is returned using a beam splitter and the signal is captured by a standard avalanche photodiode.

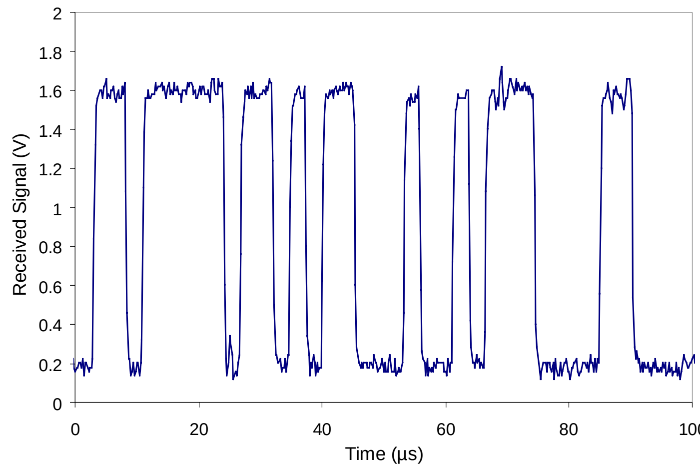


Figure 12. A sample of the return from data captured in flight using the NRL MQW retroreflector is shown. As long as the link was maintained through accurate pointing and tracking, signal amplitudes were high enough to maintain a robust communications link.

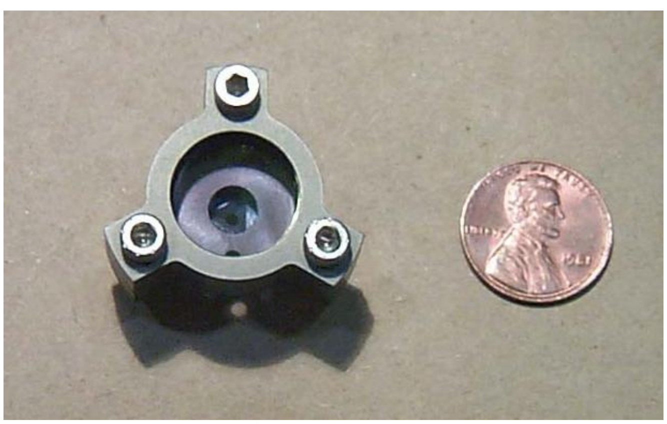


Figure 13. The new mount for upcoming tests is shown. The unit which houses the retro, MQW shutter, cover plate, leads and bolts is 10 grams. The unit will be configured with several more into an array to increase the payload FOV and further relax onboard pointing and tracking requirements.